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ELECTRICAL PERFORMANCE OF A 2- TO 10-KILOWATT BRAYTON ROTATING UNIT

by Robert C. Evans and Sheldon J. Meyer

Lewis Research Center
Cleveland, Ohio 44135

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16. Abstract

The Brayton rotating unit with electronic voltage and speed control was operated as part of a closed loop laboratory test facility. This report presents the results obtained from electrical tests conducted during 475 hours of operation at output power levels ranging from 1 to 15 kW and lagging power factors of 0.73 to 0.95. The level of neutral current was not constant but varied with parasitic load. Small load fluctuations were observed as each speed controller began to apply parasitic load and at the 3-kW load point for each unit. The electrical system was stable for all transient useful loads investigated. The alternator armature windings operated with higher temperatures at design load (10.7 kW, 0.75 power factor) than predicted.

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SUMMARY

The Brayton rotating unit (BRU) with electronic voltage and speed controls was operated as part of a closed loop laboratory test facility. The purpose of the test was to obtain performance data for the BRU when operating at design turbine inlet temperature and speed, and with loads on the alternator from 1 to 15 kilowatts. This report presents the results obtained from operation of the alternator, voltage regulator, and electronic speed control over this load range.

The gain (applied parasitic load/frequency error) for the speed control was constant for over 475 hours of operation with loads ranging from 1 to 15 kilowatts. The speed control caused neutral current which varied as parasitic load changed. Load fluctuations were observed as each speed controller began to apply parasitic load and at the 3-kilowatt load point for each unit. These fluctuations reached a maximum of 0.3 kilowatt peak to peak without resulting in measurable changes in BRU speed. The electrical system was stable for all transient useful load changes to 83 percent of the alternator net output power. The voltage regulator performed within design specifications. The maximum recovery time was 2.3 seconds for a step useful load application of 8.9 kilowatts at unity power factor. The maximum recovery time for removal of the same useful load was 1.7 seconds.

The maximum service temperature of 220° C for the armature winding insulation was exceeded at alternator net power outputs above 11.4 kilowatts, 0.95 lagging power factor, with a coolant flow rate 25 percent higher than design.

The voltage regulator and the speed control experienced no deterioration of performance during the test period. At the conclusion of these tests, they had operated in the hot test facility for a total of 1000 hours.

INTRODUCTION

The Lewis Research Center is currently engaged in a technology program to develop components for Brayton cycle space power systems (ref. 1). As a part of this program, a single-shaft turbine-compressor-alternator with an electronic speed and voltage control system was procured under contract from AiResearch Manufacturing Company of Arizona for evaluation at Lewis Research Center. The turbine-compressor-alternator which comprises the rotating component of the Brayton cycle power system is called the Brayton rotating unit (BRU). The working fluid is a mixture of helium and xenon with an average molecular weight of 83.8. The alternator is designed for 10.7 kilowatts, 0.75 lagging power factor, 120/208 volts, three phase, 1200 hertz at 36 000 rpm.

Preliminary tests were conducted on the BRU using working fluids of krypton and argon. Data from these tests can be found in references 2 and 3.

This report presents the results obtained from electrical tests conducted during 475 hours of operation using the design working fluid of helium and xenon. The electrical tests were as follows: application of balanced three-phase alternator loads, application of unbalanced loads, and application and removal of transient loads.

ALTERNATOR

A photograph and schematic of the BRU are shown in figures 1 and 2, respectively. The turbine rotor and the compressor impeller are mounted on opposite ends of a common shaft, with the alternator rotor in the center. The two journal bearings are located just outboard of each end of the alternator rotor. The thrust bearing is located between the compressor impeller and the compressor end journal bearing.

The design specifications for the alternator are presented in table I. The alternator is a solid-rotor, four-pole, modified Lundell (ref. 4). Figure 3 is a sectional view of the alternator. The rotor consists of two separate magnetic sections made of SAE 4340 brazed to a nonmagnetic separator made of Inconel 718.

The alternator utilizes two fields. The shunt field is supplied by the voltage regulator to maintain the output voltage at the rated level. The series field is supplied by the series field exciter. Its output is proportional to the alternator three-phase line currents. Under three-phase fault conditions, the series field exciter would supply the excitation necessary to maintain short circuit current for the time interval needed for circuit protection devices to operate. Also, use of this exciter reduces the power requirements placed on the voltage regulator by supplying part of the total field excitation required by the alternator under load.

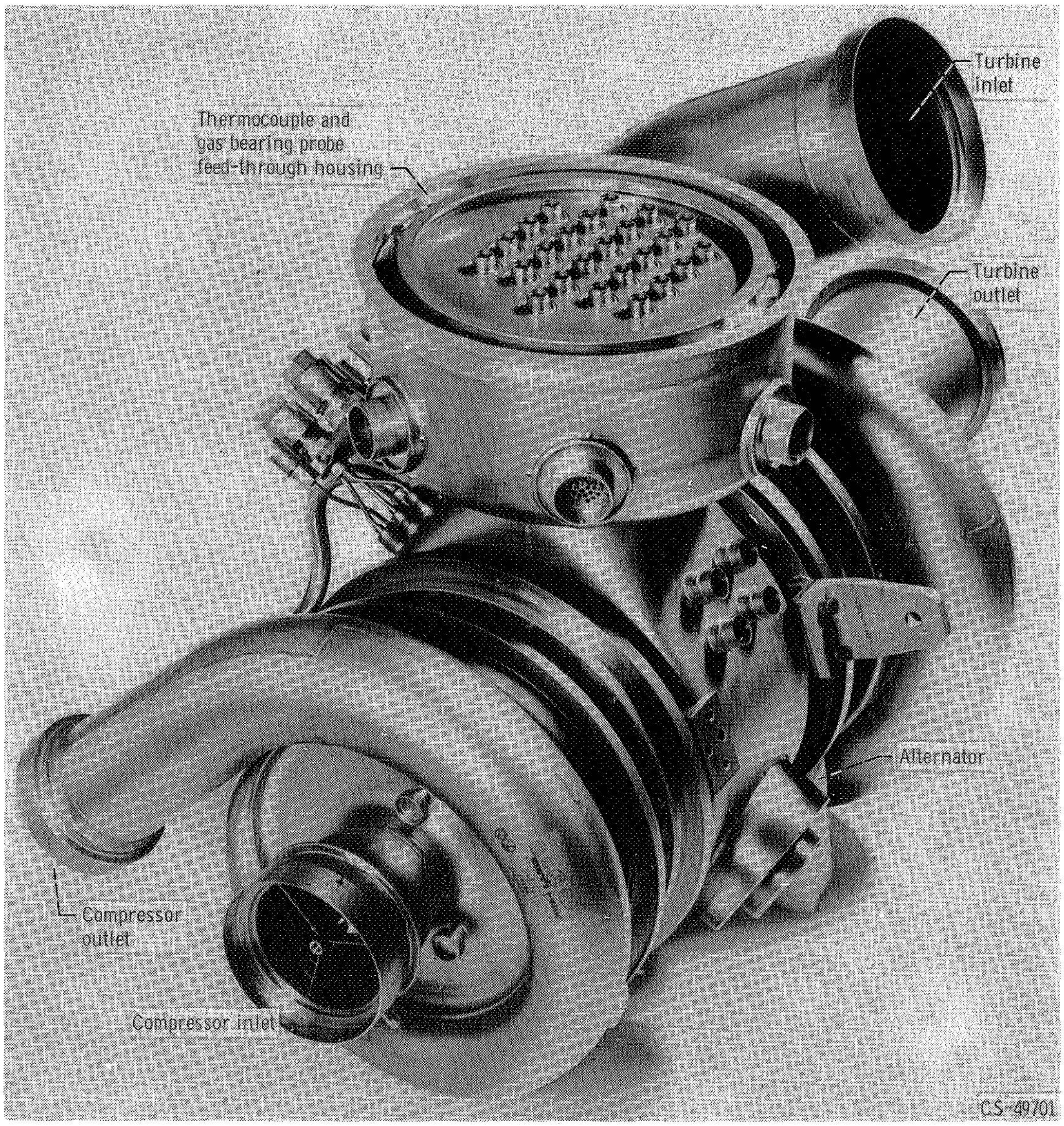


Figure 1. - Brayton rotating unit (BRU).

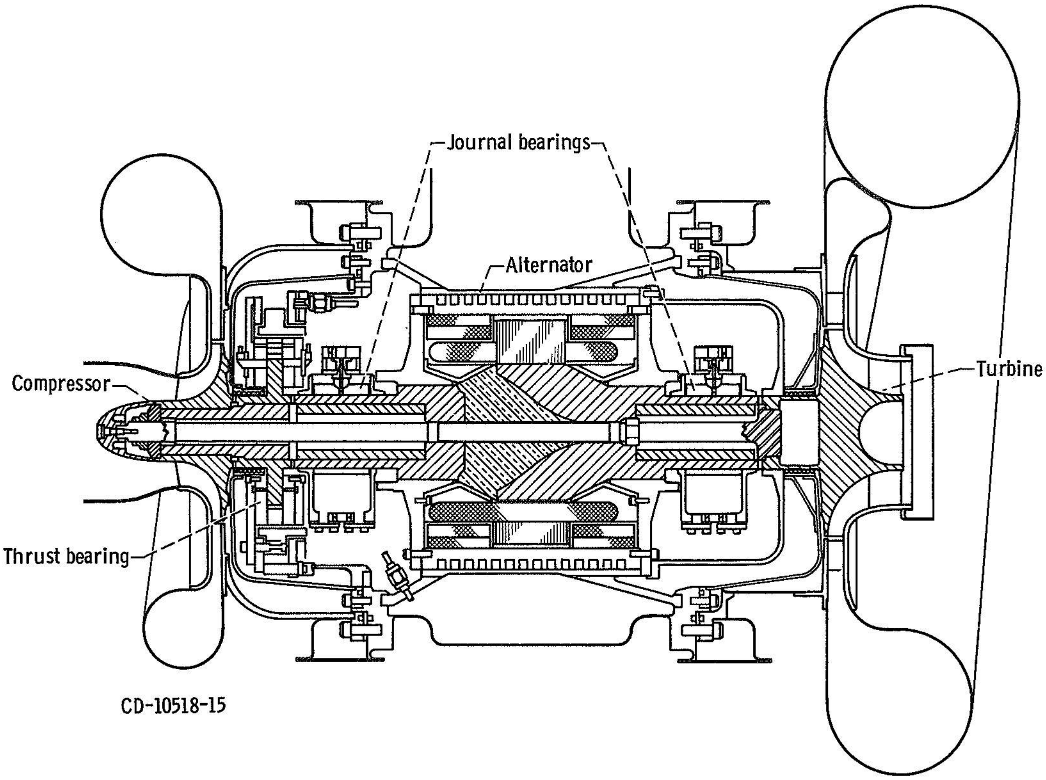


Figure 2. - Schematic of BRU.

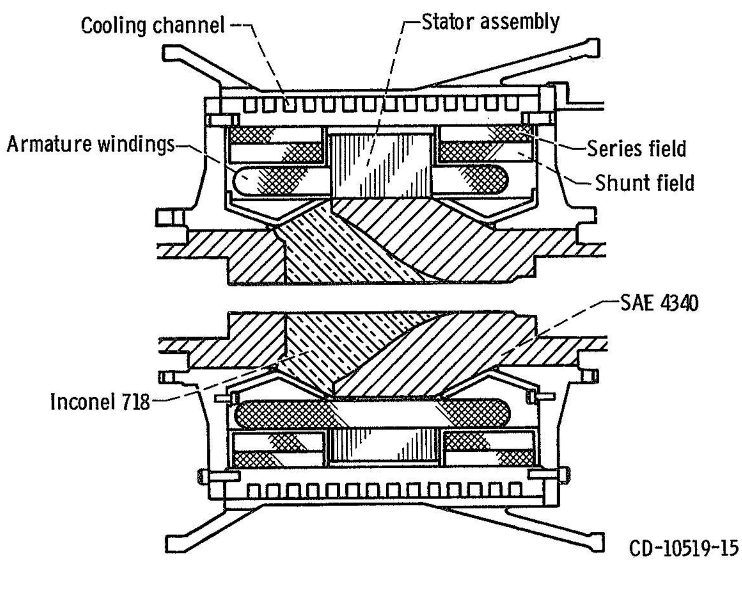


Figure 3. - Sectional view of BRU alternator.

TABLE I. - ELECTRICAL COMPONENT DESIGN SPECIFICATIONS

Alternator	
Power output, kW	10.7
Phase	3
Power factor	0.75
Voltage, V	120/208
Frequency, Hz	1200
Liquid coolant	Dow Corning 200
Liquid coolant inlet temperature, ^{o}C	21
Liquid coolant flow rate, lb/sec (kg/sec)	0.12 (0.054)
Winding insulation temperature rating, ^{o}C	220
Voltage regulator-exciter	
Regulation (for balanced loads from 10 percent to full load at rated power factor and frequency)	120 V±1 percent
Response time (within ±5 percent of steady-state voltage) for application or removal of one per unit load, sec	1/4
Voltage regulator internal loss (at 120-V line to neutral and one per unit alternating line current), W	41
Speed control	
Speed regulation (for a change in load from 10 percent to full load), percent	±1
Response time (within ±2 percent of steady-state speed) for application or removal of one per unit load, sec	1
Internal losses for each unit (minimum total parasitic load), W	13

Two separate helical channels are machined into the alternator outer frame assembly for cooling the field and armature windings. Each passage can be independently supplied with coolant.

VOLTAGE REGULATOR

The design specifications for the voltage regulator-excitor are included in table I. A block diagram of the voltage regulator (VR) is presented in figure 4. The VR uses as its source of power the three-phase alternator output. A solid state switching circuit

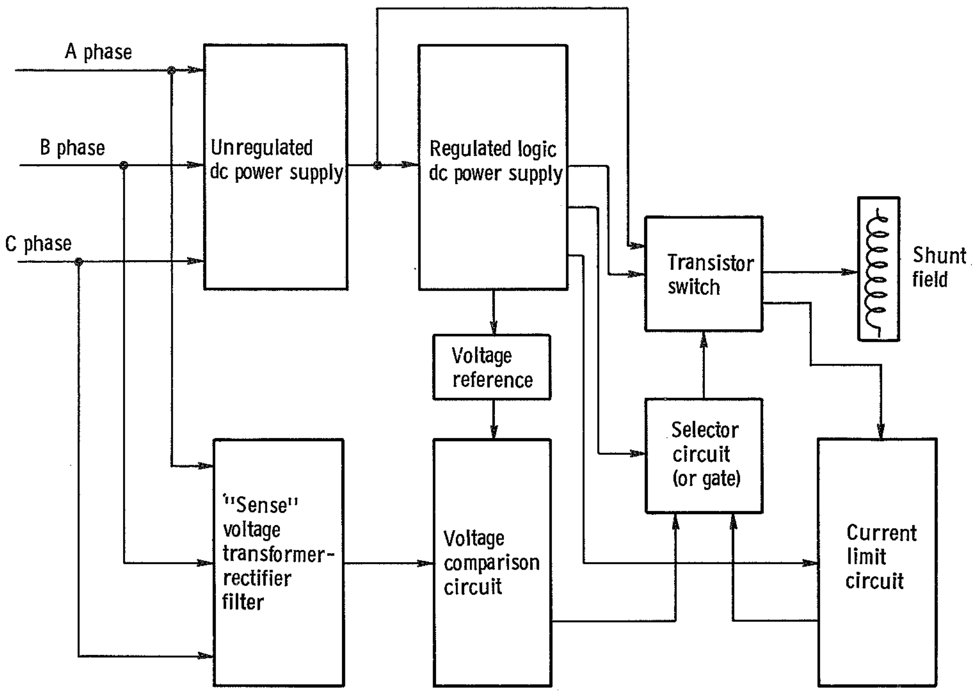


Figure 4. - Block diagram of voltage regulator (VR).

connects the shunt field winding to the unregulated dc power supply. The transistor switch is activated by an error voltage obtained from the voltage comparison circuit. The switch is operated at a rate equal to the ripple frequency of the half-wave rectified, three-phase alternator voltage (ref. 5). The current limit circuit was adjusted to limit shunt field current to approximately 6 amperes when the alternator line-to-neutral voltage is between 60 and 118 volts.

ELECTRONIC SPEED CONTROL

BRU speed control is obtained by automatically varying the electrical load on the alternator in proportion to the frequency error above 1200 hertz. This variation in load is performed by three speed controllers that vary the line-to-neutral voltage across the parasitic load resistors (ref. 5). The first speed controller can be adjusted to proportionally apply up to 6 kilowatts of parasitic load for approximately the first 1 percent of frequency error above 1200 hertz. The second and third controllers proportionally add up to 6 kilowatts each for approximate frequency error ranges of 1 to 2 percent and 2 to 3 percent, respectively.

APPARATUS

A diagram of the test loop is shown in figure 5. The test loop which is described in reference 2 is basically a closed Brayton cycle power system. The gas bearing supply line is for external pressurization of the bearings during startup and shutdown to prevent rubbing. Above 30 000 rpm, the bearings are made completely self-acting by the removal of external pressurization.

Figure 6 shows a block diagram of the electrical system. Also shown is the location

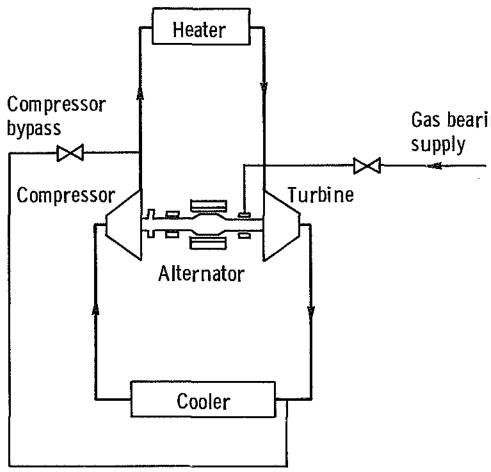


Figure 5. - Diagram of test loop.

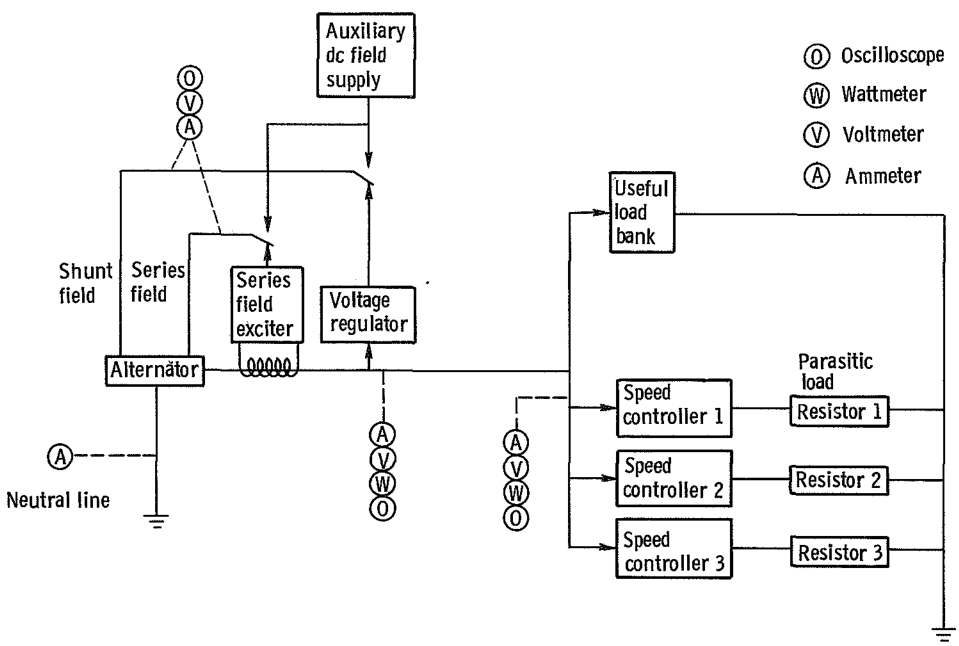


Figure 6. - Block diagram of electrical system.

of the instrumentation used to measure electrical system performance.

The useful load bank can provide balanced and unbalanced resistive and/or inductive loads to the alternator.

The parasitic load bank is a resistive load bank preset to dissipate a maximum of 6 kilowatts from each speed controller.

The auxiliary field supply is a continuously variable dc power supply which may be optionally connected to shunt and series fields to provide emergency excitation.

INSTRUMENTATION

The instrumentation used to measure the electrical performance can be classified as either steady state or transient. The steady-state instruments were selected for their high level of accuracy. These instruments have a very slow response time for step input signal changes, approximately 2 seconds or more, but have accuracies ranging from 0.1 to 1.0 percent of full scale. The instruments used for transient system conditions were selected for their fast response time. These instruments have response times less than 0.005 second for step input signal changes from zero to full scale. Their accuracies range from 2 to 5 percent of full scale.

The steady-state instruments are as follows. Electrodynamometer wattmeters with a frequency range of dc to 2500 hertz were used to measure real power. These meters have a dc output proportional to power. Current and voltage were measured using rms thermocouple-type meters with a frequency range from 50 hertz to 1 megahertz. These meters have a dc output proportional to their ac signal input. The line frequency was measured with a frequency to dc converter. Turbine flowmeters were used to measure the coolant flow rate. Chromel-Alumel thermocouples were used to measure all alternator temperatures.

The instrumentation used to study transient operation is as follows. The ac voltages and currents were measured using rectifier-type meters. The dc outputs from these meters were recorded on an oscillograph using 3300-hertz galvanometers.

PROCEDURE

Electrical tests were conducted during startup, shutdown, and steady-state operation of the loop to determine the operating characteristics of the electrical components in a Brayton cycle power system.

During startup as described in reference 2, VR operation as a function of speed was studied. The speed control was connected to the alternator but not operating at speeds

below 36 000 rpm. The useful load bank was not connected. Shunt field current, alternator line-to-neutral voltage, and BRU speed were recorded on an oscillograph.

During steady-state loop operation as described in reference 6, electrical tests were conducted as follows. Four different types of load conditions were applied to the alternator: (1) all parasitic load, (2) parasitic load and balanced three-phase useful loads, (3) parasitic load and single-phase useful loads, and (4) parasitic load and transient useful loads. The first series of tests were with all parasitic load. The alternator output was varied from 1 to 15 kilowatts by controlling the mass flow rate to the turbine. At each alternator output power level, the BRU was allowed to reach a steady-state temperature level before data were taken. This was done to obtain alternator internal temperatures for this load range. The coolant flow rate was held constant at 0.15 pound per second (0.07 kg/sec). At the 15-kilowatt level, the inlet coolant temperature was lowered from 20° to 14° C to check the effect on the alternator temperatures.

The second series of tests was taken to study the effect of using a combination of balanced three-phase useful loads and parasitic load. Small increments of load were added to the alternator, using the useful load bank, until the BRU speed decreased to 36 000 rpm (approximately zero speed control frequency error). In addition, at a nominally constant alternator power output of 10.5 kilowatts, useful loads up to 1.4 kilowatts were added to one phase of the alternator to study the effect of unbalanced loading.

The transient load tests were made at alternator power output levels of 4.1, 7.0, and 10.7 kilowatts. Balanced three-phase useful loads were added and removed in step increments to check the dynamic response of the electrical system. The maximum useful load applied at each output level was the load that would decrease the BRU speed to 36 000 rpm.

RESULTS AND DISCUSSION

The electrical performance of the alternator, VR, and electronic speed control will be discussed for the various tests performed. The discussion will be divided into the following areas: (1) line voltage and field excitation variations with speed, (2) parasitic speed control alternator loading characteristics, (3) steady-state useful loads, (4) transient useful loads, and (5) alternator temperatures.

Line Voltage and Field Excitation Variations with Speed

Figure 7 shows the variations in alternator line-to-neutral voltage with speed. The voltage generated by the alternator at speeds below 10 000 rpm is due to the presence of

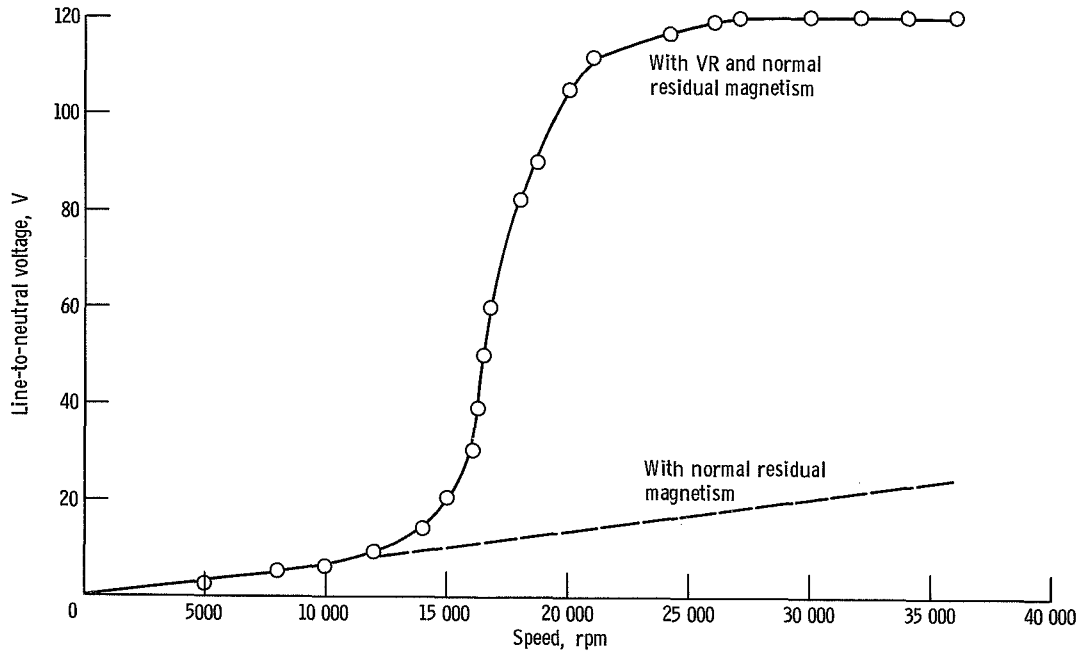


Figure 7. - Variation in line-to-neutral voltage with BRU speed.

the residual magnetism. Above 10 000 rpm, the dashed line represents the voltage generated with the normal residual field if the VR is not connected. The solid line above 10 000 rpm represents the voltage generated with the VR operating normally. At 10 000 rpm, the line voltage has built up to approximately 7 volts rms. This is high enough to turn on the VR, and it begins to supply current to the shunt field. Figure 8 shows the output current from the VR to the shunt field as the speed was increased. That portion of the curve between 16 800 and 24 000 rpm is the region where the VR limits shunt field current to a nominal 6 amperes.

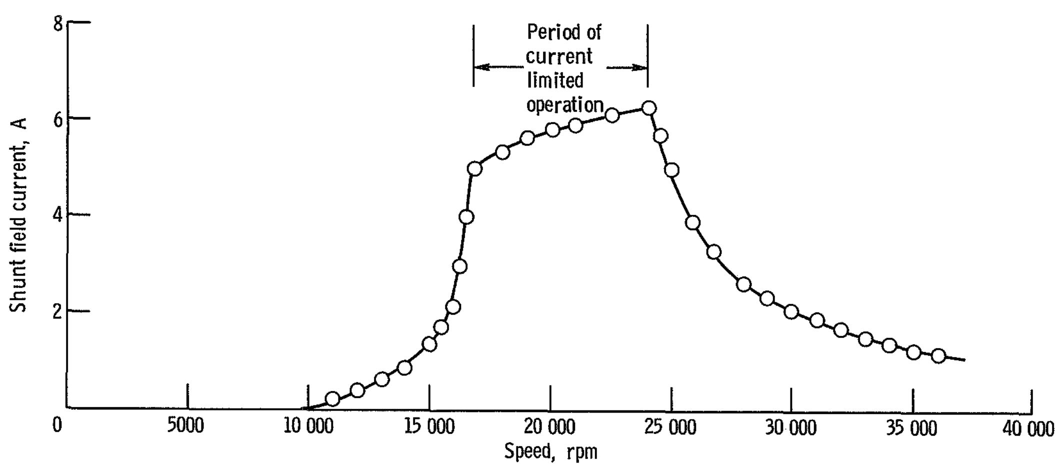


Figure 8. - Variation in shunt field current with BRU speed.

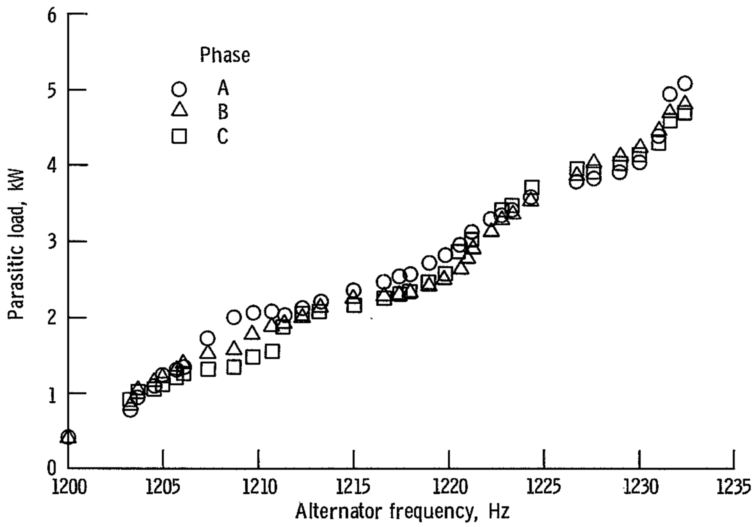


Figure 9. - Phase loading of BRU alternator by parasitic speed control.

Parasitic Speed Control Alternator Loading Characteristics

Phase loading for the speed control is given in figure 9. The degree of balance between the phases is not constant but changes with frequency error. This is due to unequal changes in the silicon controlled rectifier firing circuit in each phase of a controller. The maximum unbalance occurs at a frequency error of approximately 9 hertz and occurs in the first speed controller. With the exception of the 1206- to 1212-hertz frequency range, the difference in parasitic phase loadings ranged from near zero to a maximum of 0.3 kilowatt over the frequency error range of 1200 to 1232 hertz and a total load range of 1.0 to 14.7 kilowatts.

Figure 10 shows alternator parasitic loading to approximately 15 kilowatts utilizing all three speed controllers. The first controller applied a total of 6.0 kilowatts at 1212 hertz, the second applied an additional 6 kilowatts at 1229 hertz, and the third supplied the remainder. This speed control gain was not affected by a total of 475 hours of operation.

Figure 11 shows the effect of net load power factor on the parasitic loading of the alternator. Net output power equals the total alternator output power minus the power required by the voltage regulator-exciter. Lower net load power factor points were obtained by adding inductively reactive useful load in parallel with the speed control. With a net output power of 10.5 kilowatts and a 0.95 lagging power factor the total parasitic load is 10.1 kilowatts at a frequency of 1223 hertz. At a lagging power factor of 0.84 and a frequency of 1223 hertz, the total parasitic load on the alternator has dropped to 9.7 kilowatts. At a power factor of 0.73 and 1223 hertz, the total parasitic load has

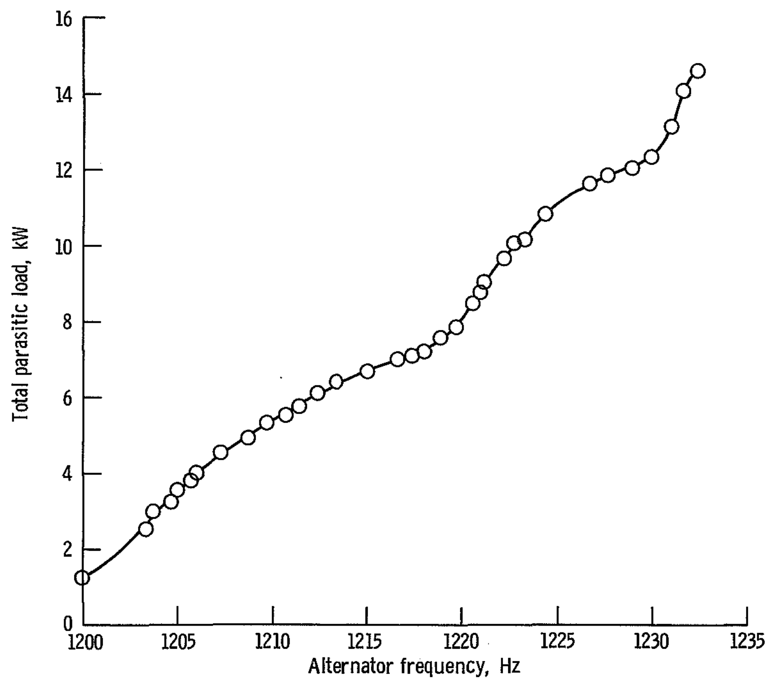


Figure 10. - Parasitic speed control alternator loading characteristics.

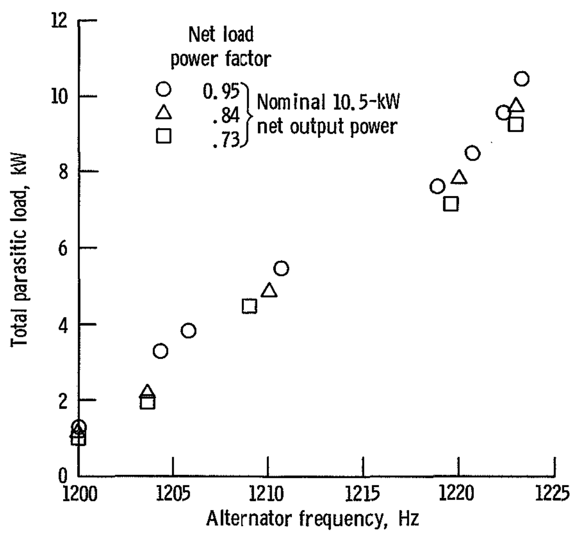


Figure 11. - Effect of net load power factor on parasitic speed control alternator loading. (Useful load = net output power - parasitic load.)

dropped to 9.3 kilowatts. This decrease in parasitic load at constant frequency error is due to an increase in voltage drop between the alternator output and the speed control input, with the decreasing power factor. Increased power losses in the alternator and in the useful load bank inductors provide for maintaining constant alternator total load and speed.

The variations in line-to-neutral voltage as a function of total parasitic loading is shown in figure 12. The voltage is the average of the line-to-neutral voltages for the

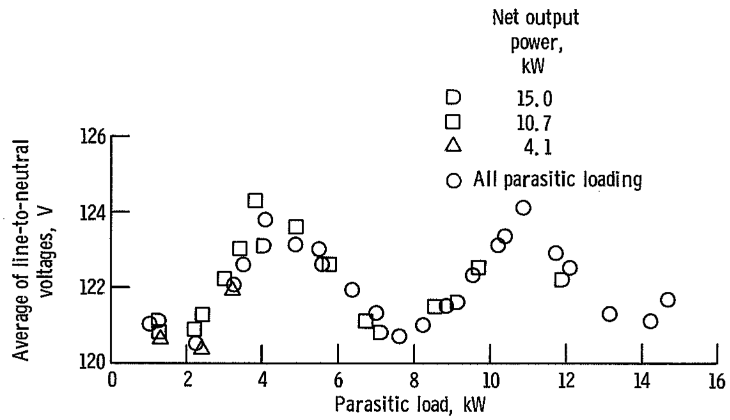


Figure 12. - BRU alternator average line-to-neutral voltage as affected by parasitic load.

three phases. Two load conditions are plotted in figure 12, (1) all loading of the alternator is accomplished with parasitic load and covers a range from 1.0 to 14.7 kilowatts, (2) the net output power is divided between the parasitic load and the useful load. In the second case, the average of the line-to-neutral voltages for net output powers of 4.1, 10.7, and 15.0 kilowatts is shown. In all cases the average voltage was determined by the amount of parasitic load on the system. Over a parasitic load range of 1.0 to 14.7 kilowatts this average voltage varied between 120.5 and 124.3 volts. Maximum voltage deviation from 120 volts was 3.6 percent.

The alternator neutral current for various parasitic and balanced useful loads is shown in figure 13. The maximum neutral current was obtained at approximately 3 kilowatts with only the first speed controller operating. A second high neutral current peak occurs at approximately 9 kilowatts with the first controller fully on and the second controller approximately 50 percent on. The trend of the curve shows that the next maximum point should be at a 15-kilowatt parasitic load. At this point the first two controllers are fully on and the third approximately 50 percent on. The line currents in the speed controller parasitic load do not completely cancel at the neutral but add to form third harmonic current. The maximum neutral current occurs when any speed controller is operating at a 90° conduction angle, approximately 50 percent on. The minimum neu-

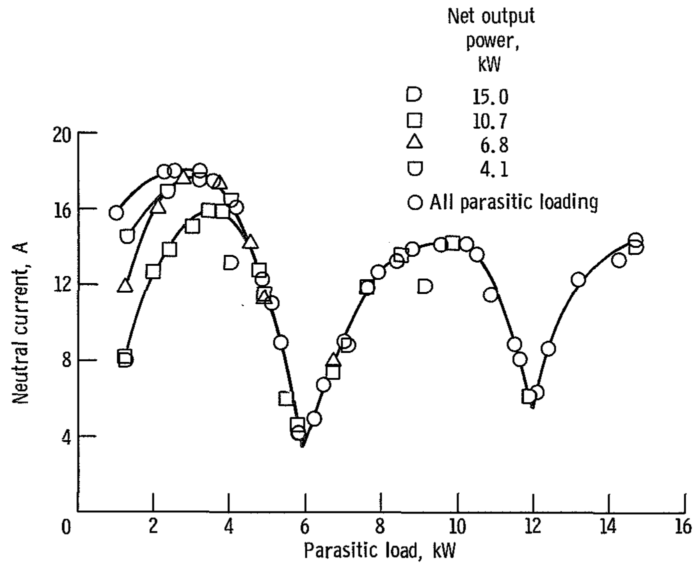


Figure 13. - BRU alternator neutral current for various useful and parasitic load levels. (Useful load = net output power - parasitic load.)

tral current levels for the complete parasitic load range are at points where the speed controllers are turned fully on or are not conducting. Minimum points are not zero because of unbalance in the speed controller firing circuits, parasitic load resistors, and small third harmonic current. Figure 13 shows the effect of useful load on the neutral current. This current decreases as useful load is applied but its effect is not significant until the total useful load is much greater than the total parasitic load. A suitably sized neutral conductor must be provided to carry this current since its maximum value approaches 45 percent of rated line current.

Parasitic load instabilities were observed at approximately 0.4, 3, 6, 9, 12, and 15 kilowatts. At the 0.4- and 3-kilowatt points, the total load varied ±0.15 kilowatt with periods ranging from 0.5 to 3 seconds. The amplitude of the fluctuations progressively decreased at the higher loads. These changes in load did not produce measurable changes in speed and were not caused by interaction between the VR and speed control. The fluctuations were also observed when the auxiliary field supply was used to excite the alternator fields. The load levels where these fluctuations occurred correspond to the neutral current maximum and minimum load points plotted in figure 13.

Steady-State Useful Loads

Figure 14 shows the effect of BRU speed on net output power for constant turbine inlet temperature. With a constant turbine inlet gas temperature, the power output from

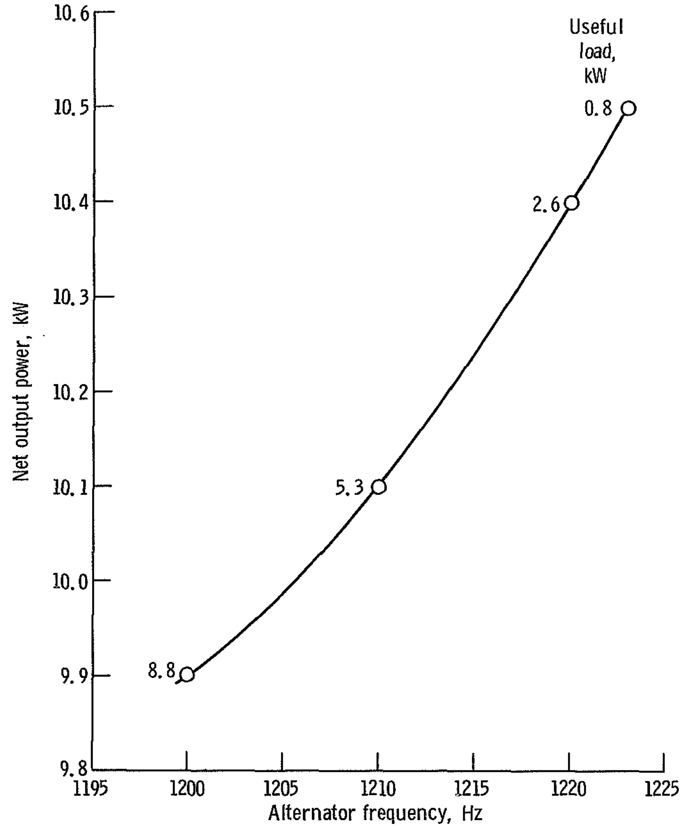
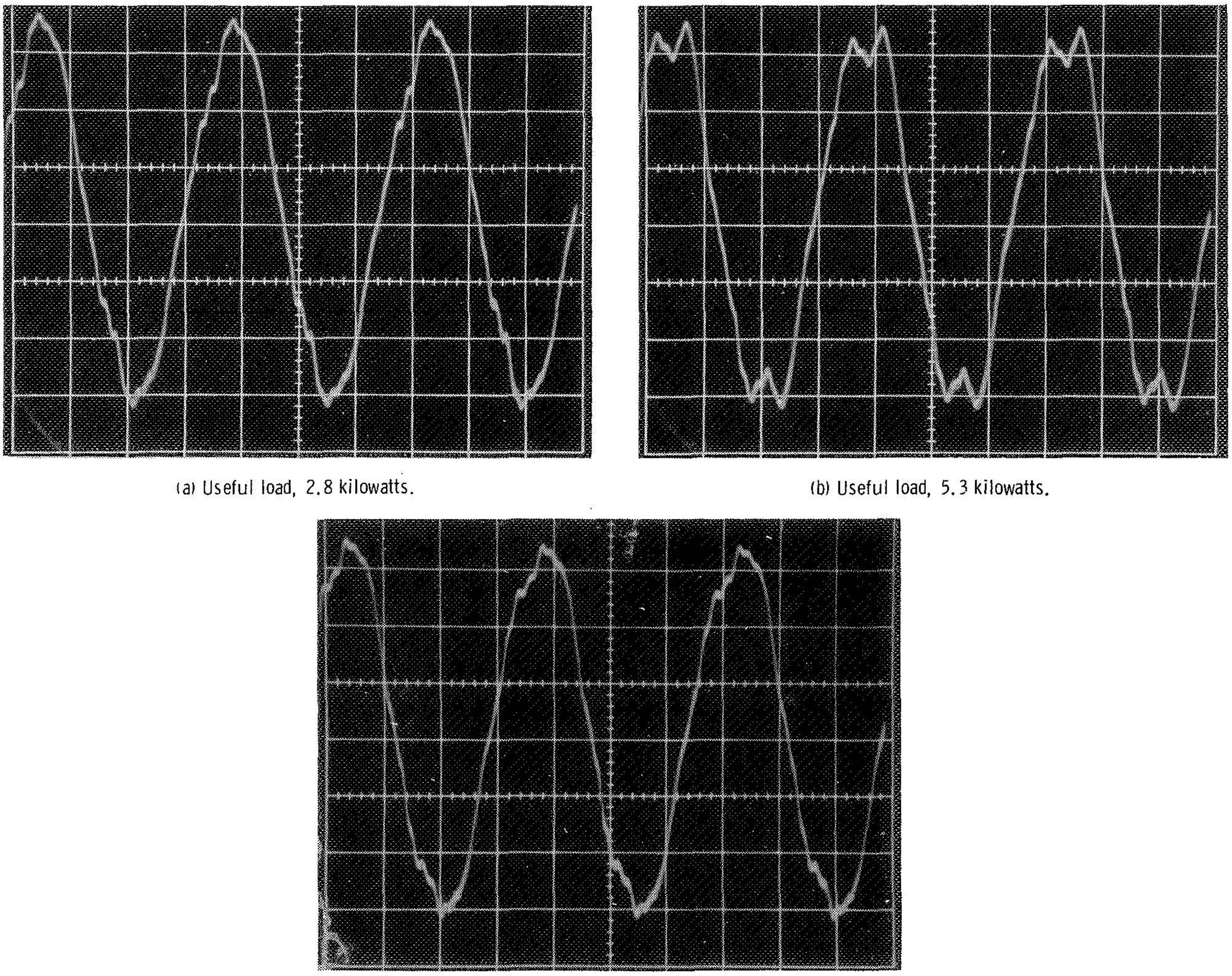


Figure 14. - Effect of alternator frequency (BRU speed) on net output power at constant turbine inlet temperature. Net load power factor, 0.84; turbine inlet temperature, 871° C; compressor inlet temperature, 24° C; constant gas inventory in system.

the turbine to the alternator will decrease if the speed decreases. This is due to the decrease in mass flow rate from the compressor (ref. 6). At a constant turbine inlet temperature of 871° C and operating with a net output power of 10.5 kilowatts with a useful load of 0.8 kilowatt, the turbine speed was 36 690 rpm. By increasing the useful load to 8.8 kilowatts and keeping the turbine inlet temperature constant, the net output power decreased to 9.9 kilowatts. This is a 5 percent decrease in net output power. When stating values of the net output power for a series of useful load changes, the word nominal will be used to indicate the net power at the start of the test series did not remain constant throughout the test.

The line-to-neutral voltage waveform photographs in figure 15 were taken at a nominal net output power of 10.5 kilowatts, 0.75 lagging power factor, for three balanced useful loads. The photographs were not calibrated and are intended only to show the waveform distortion which occurs as the silicon controlled rectifiers in each speed controller fire. Different degrees of distortion are produced for each load as the firing

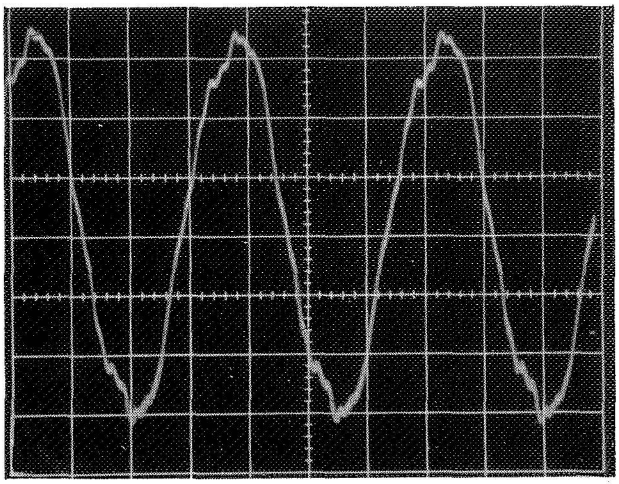


(a) Useful load, 2.8 kilowatts.

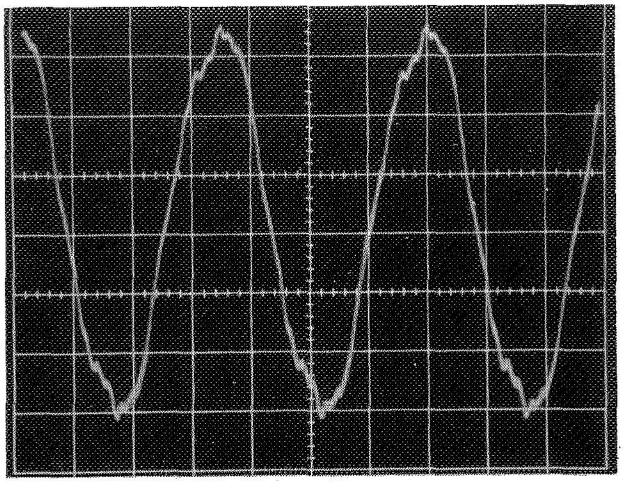
(b) Useful load, 5.3 kilowatts.

(c) Useful load, 7.8 kilowatts.

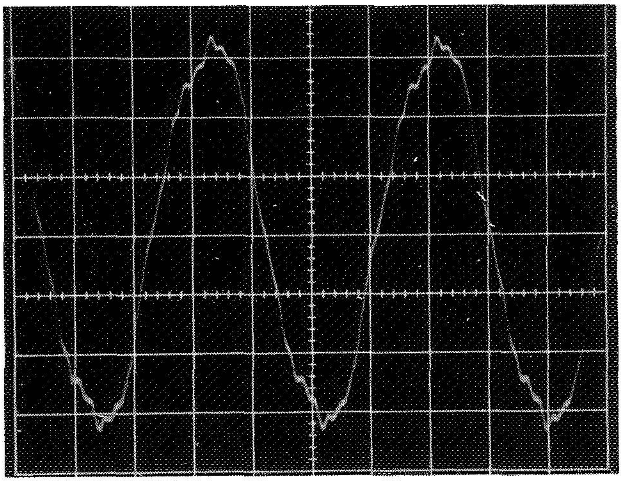
Figure 15. - Oscilloscope traces of alternator line-to-neutral voltage. 10.5- Kilowatt nominal net output power; 0.78 power factor.



(a) Net load power factor, 0.78.



(b) Net load power factor, 0.84.



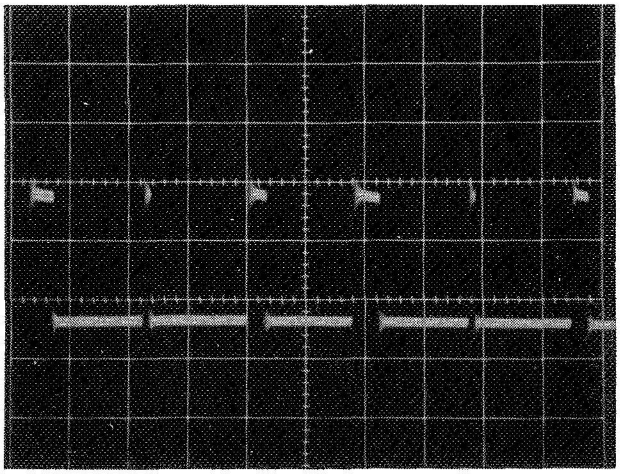
(c) Net load power factor, 0.90.

Figure 16. - Oscilloscope traces of alternator line-to-neutral voltage. 10.5- Kilowatt nominal net output power; useful load, 7.8 kilowatts.

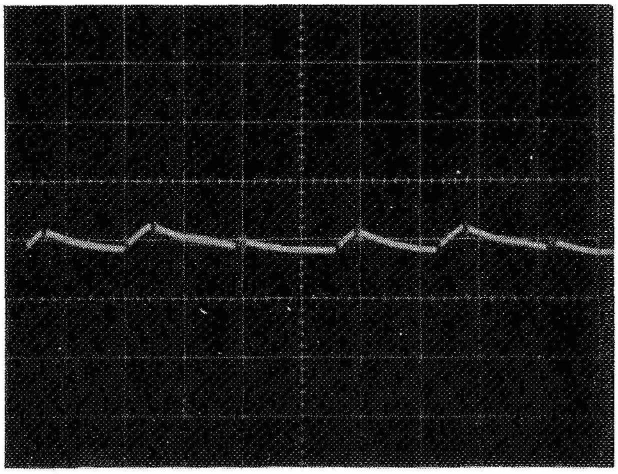
point (conduction angle) changes. Figure 16 shows the line-to-neutral voltage waveforms at a net output power of 10.5 kilowatts, with lagging power factors of 0.78, 0.80, and 0.90. No apparent change in the waveform distortion occurs as the power factor is varied. The observed voltage waveform distortion will not usually affect operation of most motors, resistance heaters, or other similar electrical loads. Certain electronic equipment may require special filters.

Figure 17 shows waveforms of the shunt field current and voltage at a 15-kilowatt parasitic load. The voltage waveform indicates VR switching on every half cycle. Pulse time duration is unequal due to the different line-to-neutral voltage magnitudes and distortion. The current waveform reflects these different voltage pulse time intervals.

At a nominal net output power of 10.5 kilowatts, useful load was added to one phase. Figure 18 shows the average line-to-neutral voltage obtained over the range of single-



(a) Shunt field voltage.



(b) Shunt field current.

Figure 17. - Shunt field voltage and current at 15-kilowatt parasitic load, 0.95 net load power factor. (Time base, 0.1 msec/cm.)

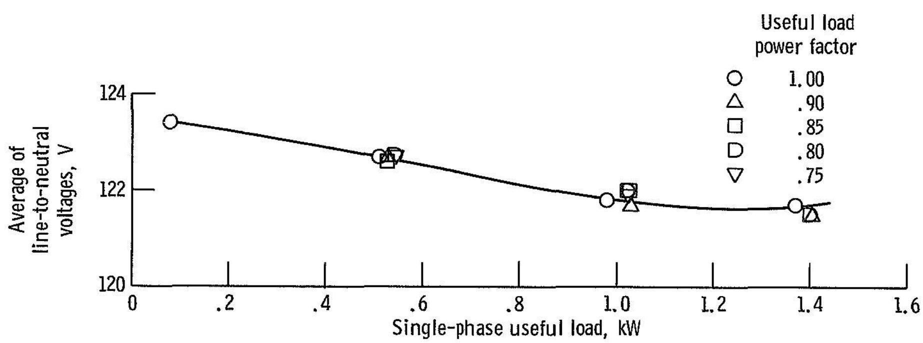


Figure 18. - Alternator average line-to-neutral voltage for single-phase useful loads. 10.5-Kilowatt nominal net output power; 0.95 power factor.

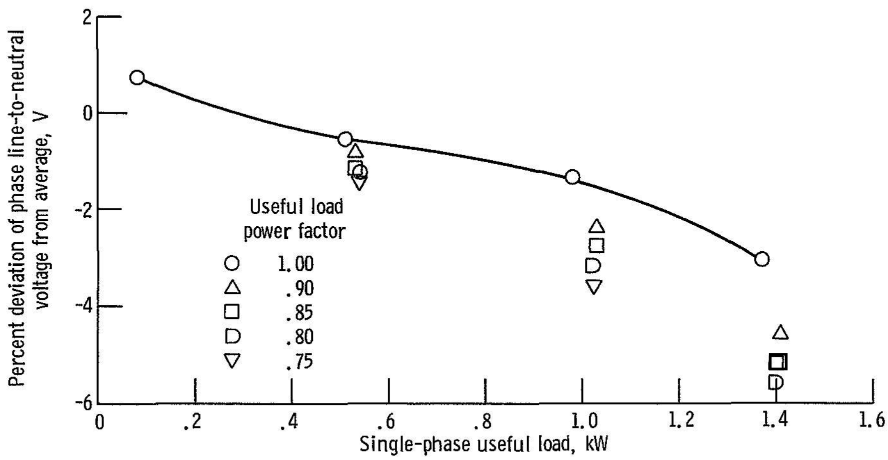


Figure 19. - Deviation of phase line-to-neutral voltage from average for single-phase loading. 10.5-Kilowatt nominal net output power; 0.95 power factor.

phase load applied at power factors from unity to 0.75 lagging. The average voltage varies less than 2.0 volts for a single-phase useful load of 1.4 kilowatts when operating with a net power output of 10.5 kilowatts. The phase voltage varied from 124 to 115 volts. Figure 19 gives the percent deviation of phase voltage from the average.

When operating the alternator at a net power output of 10.5 kilowatts with parasitic loads between 8.5 and 10.5 kilowatts, the neutral current is approximately 14 amperes. If unbalanced useful loads are added, the neutral current increases above this level. For a single-phase useful load of 1.4 kilowatts, the neutral current reached a value of 18.9 amperes. Figure 20 shows the effect of this single-phase loading on the neutral current.

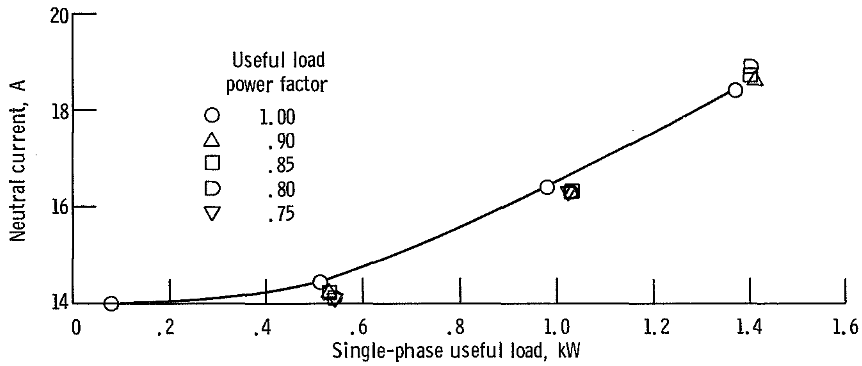


Figure 20. - Alternator neutral current for single-phase useful loads. 10.5-Kilowatt nominal net output power; 0.95 power factor.

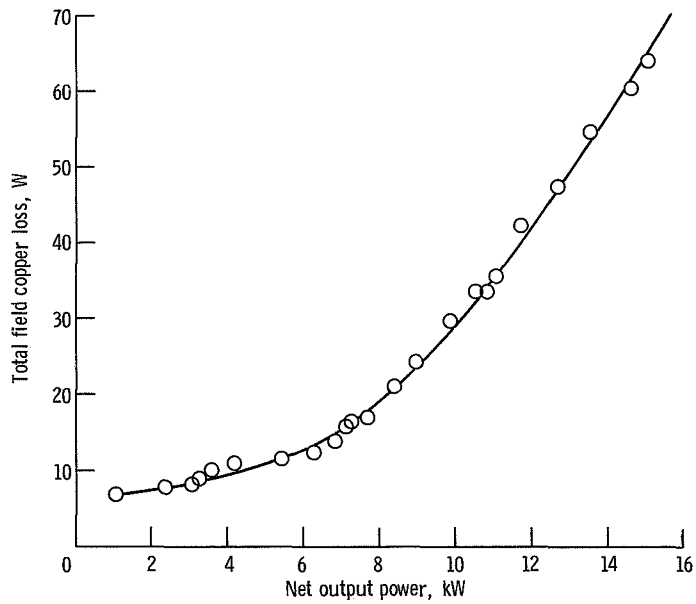


Figure 21. - Total BRU alternator field losses for net output power at 0.95 power factor.

The total alternator field copper losses for net output powers to 15.0 kilowatts is shown in figure 21. The loads are at a power factor of 0.95 lagging. Figure 22 shows the change in field copper loss with changes in power factor at a constant net output power of 10.0 kilowatts with a 1.2-kilowatt parasitic load.

Transient Useful Loads

Recovery time as defined in this report is the time required for the alternator load to reach within ±2 percent of the final value after the initiation of a useful step load change.

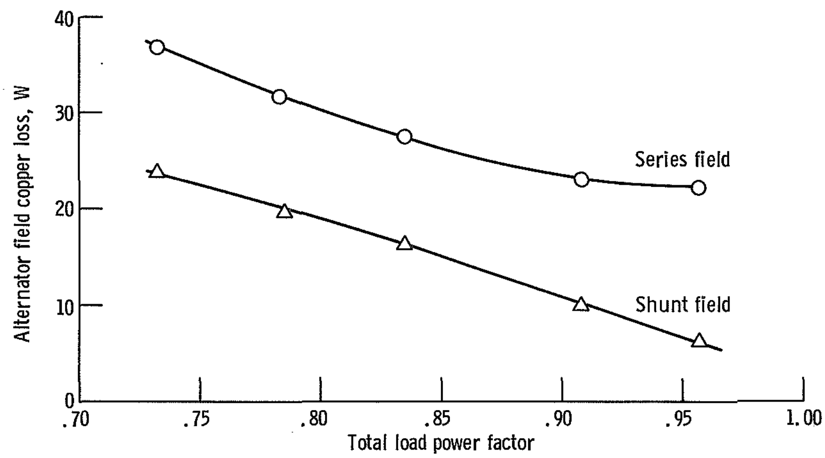


Figure 22. - Field losses at 10.0-kilowatt nominal net output power for various net load power factors. Parasitic load, 1.2 kilowatts; alternator frequency, 1200 hertz; speed, 36 000 rpm.

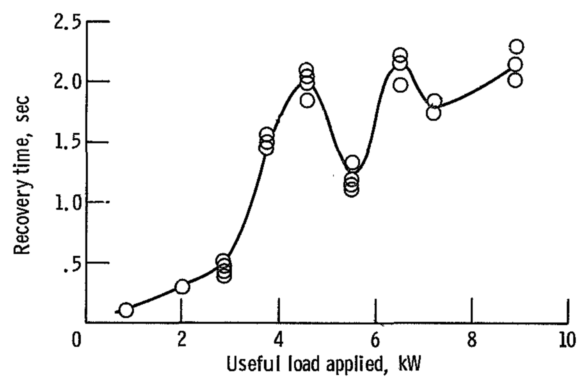


Figure 23. - Time required for alternator load to reach within 2 percent of final value after instantaneous application of unity power factor useful loads. 10.7-Kilowatt nominal net output power.

Figure 23 gives the recovery time as a function of balanced, three-phase, unity power factor, useful load applied in steps to the system when operating at a nominal alternator output of 10.7 kilowatts. The recovery time for loads from 0.9 to 2.0 kilowatts was repeatable within 0.05 second. Recovery time for loads above 2.0 kilowatts varied as much as 0.3 second for the same load application. The maximum recovery time was 2.3 seconds for a stepped load of 83 percent of the net output power.

Figure 24 gives recovery time for the step removal of useful load while the system was operating at the same nominal load of 10.7 kilowatts. The recovery times for step useful load removal are less than those for step load application. The recovery time for step load removal was repeatable within 0.2 second for all levels.

At the instant a useful step load is applied to the alternator, the total load is the sum of the applied load and the parasitic load. This results in a momentary increase in line current. This transient condition exists until the alternator speed begins to decrease and the speed control begins reducing the parasitic load. At the instant of removal of useful load, the line current momentarily decreases until the speed increases to a level where the speed control applies enough parasitic load to maintain a constant speed. Figure 25 gives the maximum value of line current reached during step changes in three-phase unity power factor useful load ranging from 0.9 to 8.9 kilowatts at a nominal net output power of 10.7 kilowatts. For this stepped useful load range, the maximum line-to-neutral voltage deviation from any previous stable value was ±2.6 percent. This deviation is within the voltage regulator-exciter specifications.

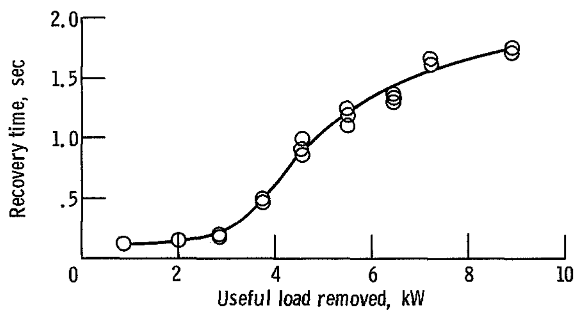


Figure 24. - Time required for alternator load to reach within 2 percent of final value after instantaneous removal of unity power useful loads. 10.7-Kilowatt nominal net output power.

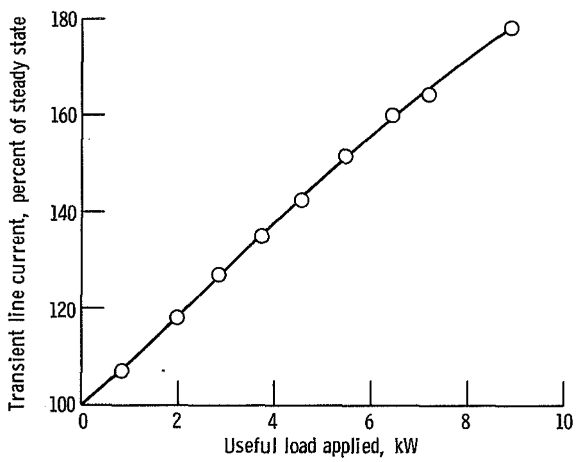
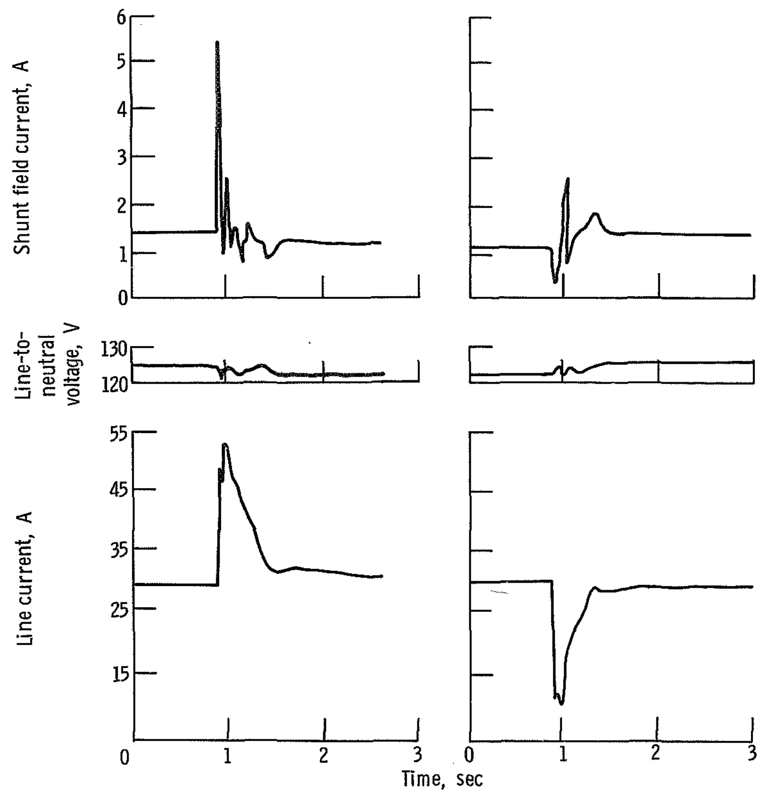


Figure 25. - Maximum line current obtained during instantaneous application of unity power factor useful loads. 10.7-Kilowatt nominal net output power.



(a) 8.9-Kilowatt step load increase. (b) 8.9-Kilowatt step load decrease.

Figure 26. - Sketch of oscillograph traces for applying and removing 8.9-kilowatt unity power factor useful load at 10.7-kilowatt nominal output power.

Figure 26 is a sketch of variations observed in the shunt field current, line-to-neutral voltage, and line current during step application and removal of 8.9 kilowatts of balanced useful load. At lower load levels, these variations changed in amplitude and time duration.

Alternator Temperatures

The alternator was designed for a constant coolant flow of 0.12 pound per second (0.05 kg/sec) at an inlet temperature of 21° C for loads from 0 to 10.7 kilowatts. Thermal maps were calculated by the contractor using this flow rate and inlet temperature. Table II gives a comparison of the calculated temperatures and the actual temperatures measured at 10.5 kilowatts. Figure 27 shows the thermocouple locations on the alternator. The coolant flow rate used in these tests was 0.15 pound per second (0.07 kg/sec) and inlet temperature 18° C rather than the design values used in the calculations. Table II shows that the armature end turn winding temperatures are approximately 20° C

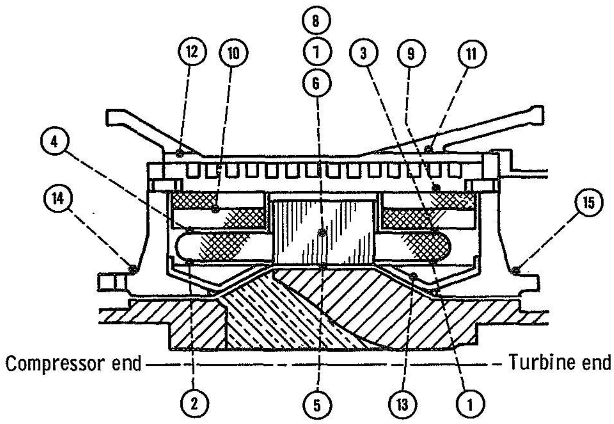


Figure 27. - Alternator thermocouple locations. (Thermocouples 6, 7, and 8 are located 120° apart circumferentially.)

TABLE II. - COMPARISON OF CALCULATED AND ACTUAL ALTERNATOR TEMPERATURES AT 10.5 KILOWATTS

Thermocouple number (see fig. 27 for location)	Alternator temperature, °C	
	Calculated	Actual
1	191	209
2	191	214
3	149	118
4	149	135
5	204	213
6	149	168
7	149	167
8	149	170
9	71	65
10	71	65
11	79	65
12	68	54
13	227	227
14	121	121
15	129	127

Operating conditions	Calculated	Actual
Alternator coolant	Dow Corning 200	Dow Corning 200
Coolant flow rate, lb/sec (kg/sec)	0.12 (0.05)	0.15 (0.07)
Coolant inlet temperature, °C	21	19
Coolant discharge temperature, °C	38	38
Power factor (lagging)	0.85	0.84

TABLE III. - ALTERNATOR TEMPERATURES FOR

THREE STEADY-STATE POWER LEVELS

[Coolant flow rate, 0.15 lb/sec (0.07 kg/sec); coolant inlet temperature, 19° C; 0.95 power factor (lagging).]

Thermocouple number (see fig. 27 for location)	Steady-state power level, kW		
	6.0	10.5	15.0
	Alternator temperature, $^{\circ}$C		
1	156	200	257
2	166	206	258
3	88	112	148
4	102	128	165
5	158	203	261
6	122	158	210
7	122	159	208
8	121	160	214
9	53	62	74
10	52	62	75
11	59	64	73
12	47	53	64
13	196	219	253
14	104	118	137
15	110	124	142

higher than predicted even with 25 percent higher coolant flow. Table III lists all the steady-state alternator temperatures for three power levels at approximately 0.95 lagging power factor. Figure 28 gives the maximum temperatures for the armature winding end turns, the armature winding at the outer diameter of the slot, and the field windings for net output power ranging from 6 to 15 kilowatts at 0.95 power factor. The armature winding insulation has a maximum service temperature limit of 220° C. This temperature limit was exceeded with a net output power of 11.4 kilowatts, at 0.95 power factor.

The alternator was designed for a 10.7-kilowatt output at power factors ranging from 0.75 lagging to unity. Figure 29 is a plot of temperatures at a nominal net power output of 10.5 kilowatts at various power factors. At power factors less than 0.78 lagging at this load level, the armature winding end turn temperatures exceed the maximum service temperature rating for the insulation.

The coolant inlet temperature was reduced from 20° C to 14° C at the 15.0-kilowatt net alternator load level to determine its effect on the alternator winding temperature. The maximum armature winding temperature, at the end turns, decreased 3° C.

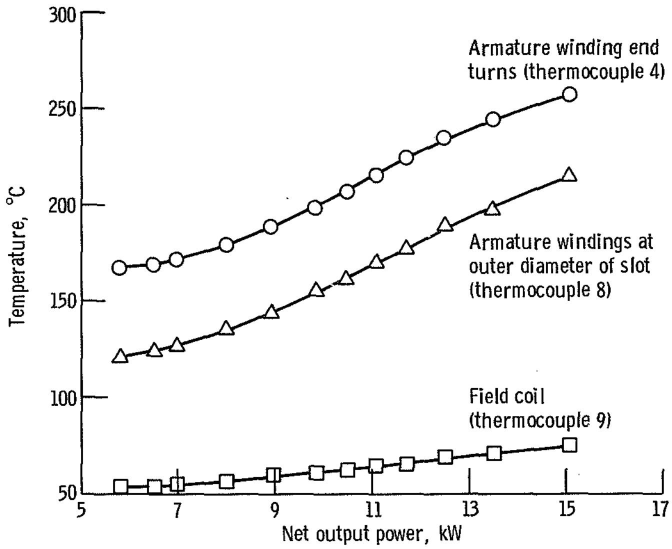


Figure 28. - Alternator temperatures at various net output power levels. Power factor, 0.95; turbine inlet temperature, 871° C; coolant inlet temperature, 18.9° C; coolant flow rate, 0.15 pound per second (0.07 kg/sec).

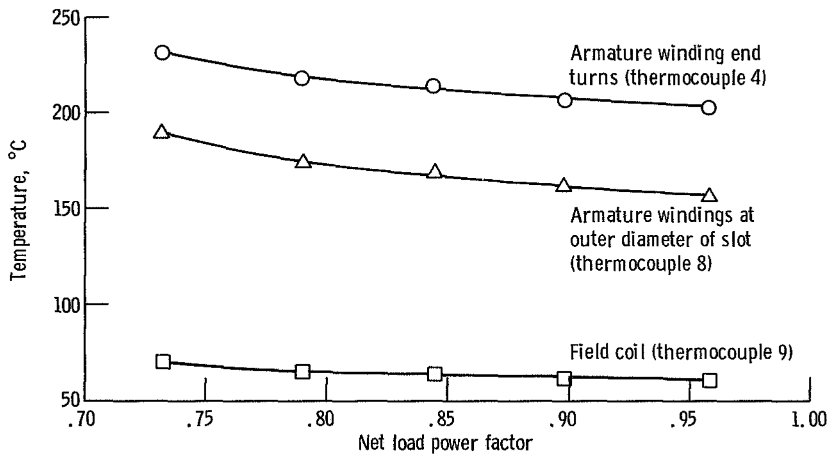


Figure 29. - Alternator temperatures at nominal net output power of 10.5 kilowatts for various net load power factors. Turbine inlet temperature, 871° C; coolant inlet temperature, 18.9° C; coolant flow rate, 0.15 pound per second (0.07 kg/sec).

SUMMARY OF RESULTS

The results of testing the Brayton rotating unit (BRU) alternator, voltage regulator-exciter, and the speed control are summarized as follows:

1. The speed control gain was found to be constant over 475 hours of operation with parasitic loads from 1 to 15 kilowatts.

2. The speed controls caused large neutral currents. The maximum current reached was 18 amperes at approximately 3 kilowatts of parasitic load.

3. Load fluctuations of approximately 0.3 kilowatt peak to peak were observed as each speed controller began to apply parasitic load and at the 3-kilowatt load point for each unit. These fluctuations did not result in measurable changes of BRU speed.

4. The electrical system was stable for all of transient useful load changes. The maximum recovery time was 2.3 seconds for application of unity power factor useful loads to 83 percent of the alternator net output power. Voltage regulator response time was within design specifications for these load conditions.

5. The maximum service temperature for the armature winding insulation was exceeded at net power outputs above 11.4 kilowatts, at 0.95 power factor. This temperature was obtained with a coolant flow rate 25 percent higher than design. An armature winding temperature of 258° C was obtained at a net output power of 15.0 kilowatts.

6. At the completion of these tests the BRU alternator, voltage regulator-exciter, and the speed control had accumulated a total of 1000 hours of operation without any deterioration in performance.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 25, 1970,
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